GUEST EDITORIAL

Climatic Effects of Air Traffic

Introduction

Lately, important research results concerning air traffic have been published, indicating that air traffic contributes to ozone formation in the upper troposphere but may contribute to stratospheric depletion. Approximately one-third of all air traffic emissions are into the lower stratosphere, with the result that a significant part of the nitrogen oxides (NO_x), sulphur dioxide (SO_2), and water, occurring there originate from air traffic. These emissions may cause additional polar stratospheric clouds consisting of nitric acid trihydrate (type 1) as well as of ice crystals (type 2) at very low temperatures. Furthermore sulphur dioxide, emitted by air traffic, is a source of additional liquid sulphuric acid/water aerosol. On the surfaces of the PSC* and aerosol particles, reactions with chlorofluorocarbon (CFC) photolysis products occur, leading to a destruction of ozone, especially in spring-time.

Furthermore, at the usual cruising altitudes of modern aircraft, the exhaust gases such as nitrogen oxides and water vapour have a strongly enhanced residence period compared with levels near the ground. These nitrogen oxides from air traffic cause an increase of smog ozone in the troposphere, which, together with the water emissions, contributes to global warming probably much more effectively than results solely from the carbon dioxide (CO_2) coming from air traffic.

Air Traffic Consequences

Growing Fuel Consumption and Pollutant Emissions

The total consumption of aviation fuel in 1993 was 170 million metric tons. This amounted to about 13% of the world's consumption of all the fuel used for transportation of all kinds. Yet despite the introduction of more economical aircraft, aviation fuel consumption increased by 50% during a recent 15 years' period (IEA [International Energy Agency], 1995).

Per kg of kerosene (1.27 litres) are produced 3.15 kg of carbon dioxide (CO_2), 1.24 kg of water, and on an average about 17 g of nitrogen oxides (NO and NO_2 = 'NO_x'), calculated as NO_2, as well as about 1 g of sulphur dioxide. Therefore in the year 1993, air traffic fuel produced 535 million tonnes of carbon dioxide, 211 million tonnes of water, about 2.9 million tonnes of nitrogen oxides, and 0.17 million tonnes of sulphur dioxide (jet engines produce 10–15 times as much NO_x per kg of fuel burned compared with heating oil).

Currently, most air traffic flies between latitudes of 20° and 70° N, at altitudes between 10 and 13 km, and at an average tropopause height of around 12 km, with the consequence that between 30 and 50% of the emissions are ejected into the lower stratosphere (Schumann, 1994).

The demand for air transport will probably double within the next 12 years, which would mean an increase of about 50% in fuel consumption by aircraft (Schumann, 1994). One reason for the steep increase in aviation fuel consumption is the low price (*e.g.* US$ 0.18 per litre of kerosene on the average). This is a consequence *inter alia* of the international exemption of tax on kerosene.

Tropospheric Ozone Increase (Smog Ozone)

In the troposphere, interaction of nitrogen oxides and hydrocarbons results in the formation of ozone (O_3) in the presence of ultraviolet (UV) light, in contrast with the situation in the stratosphere where nitrogen oxides decrease the ozone. The borderline between increase and decrease varies, depending on latitude and season, between an altitude of about 12 and 14 km (Douglass *et al.*, 1991). This means that below such an altitude, air traffic contributes to ozone and photochemical smog and subsequently to global warming. Air traffic has increased the ozone concentration by 5 to 12% between altitudes of 8 and 12 km at latitudes north of 30° N. Owing to the low temperatures at this altitude, the absorption of infrared radiation from the Earth by ozone (as well as by other 'greenhouse' gases) has an especially strong global-warming effect (Beck *et al.*, 1992; Johnson *et al.*, 1992; Schumann, 1994).

Nitrogen oxides produced by lightning are estimated to include about 16 million tons of NO_2 per year (Schumann, 1994), most of which is washed out by rain as nitric acid within hours or days. On the other hand, nitrogen oxides and nitric acid at the usual flight-altitude (*see* above) have a much longer residence time, except in tropical regions.

Stratospheric Ozone Decrease and 'Holes'

According to a NASA report (Prather *et al.*, 1992), north of 40°N about 25% of the nitrogen oxides in the stratosphere at altitudes between 12 and 28 km originate from air traffic. In the stratosphere, ozone is produced from oxygen by absorption of 'hard' UV radiation. Between 1 and 3 million tonnes per year of 'natural'

* Polar stratospheric clouds. — Ed.

Environmental Conservation, Vol. 22, Nr 3, Autumn 1995 — © 1995 The Foundation for Environmental Conservation — Printed in Switzerland

nitrogen oxides (calculated as NO_2) are also produced in the stratosphere (from N_2O under the influence of UV light). At the same time stratospheric ozone is catalytically destroyed by NO_x radicals. This results in a relatively stationary state as regards ozone concentration. Additional anthropogenic NO_x, and especially chlorofluorocarbons (CFCs), will decrease the stationary-state value (we should remember that chlorofluorocarbons may have lifetimes of around a hundred years in the stratosphere, and that they contribute as to about 25% in the global warming effect of the 'greenhouse' gases).

Furthermore, additional water and sulphur dioxide from air traffic in the stratosphere may contribute to ozone destruction by heterogeneous reactions on sulphuric acid/water aerosols (Hofmann & Oltmans, 1992). Satellite measurements of the stratospheric ozone near a latitude of 50° N have shown that the natural safety-shield of ozone, protecting life on Earth against UV light, decreases by 0.5–0.8% per year (Stolarsky *et al.*, 1991). The extent of the contribution to this decrease by air traffic has not yet been quantified. It should also be noted that the climate impact of ozone loss in the stratosphere depends strongly on the altitude at which this loss occurs and causes a cooling on the surface of the Earth ; it may even be warming if the loss occurs at heights above 30 km, though in all cases it leads to a cooling of the stratosphere.

According to the present state of knowledge, a key reaction above about 25 km altitude is the photolytic formation of halogen radicals from CFCs and other halogenated hydrocarbons under the influence of short-wave solar UV radiation. The most important halogen radicals in this respect are atomic chlorine (Cl) and chlorine oxide (ClO). These can destroy ozone catalytically, although they mainly react with methane (CH_4) and NO_2 to form hydrochloric acid (HCl) and chloronitrate ($ClONO_2$), which latter substances slowly reach lower altitudes.

On the particles' surface of polar stratospheric clouds (PSCs) three chlorine species — dimeric chlorine (Cl_2), hypochloric acid (HClO), and chloronitrite (ClONO) — are formed from the reaction of HCl and $ClONO_2$. These molecules dissociate to form chlorine radicals at the end of the Antarctic winter under the influence of sunlight. They catalytically destroy ozone *via* ClO radicals, leading to the so-called 'ozone hole'. PSCs consist either of solid nitric acid trihydrate (HNO_33H_2O, called type 1) or frozen water (type 2) or liquid aerosols of sulphuric acid/nitric acid/water (Tabazadeh & Turco, 1993; Carslaw *et al.*, 1994; Drdla *et al.*, 1994).

The additional NO_x and the approximately 80 million tonnes of water emitted annually by air traffic into the usually very dry stratosphere constitute a further increase of PSCs and therefore contribute to the 'ozone holes'.

The first 'ozone hole' was detected by the British Antarctic Survey in the early 1980s at altitudes between 12 and 26 km over the Antarctic region and lately less-intense ozone decreases have been found also in the Arctic region. In the near future more pronounced and wider ozone losses are also expected in the northern hemisphere, mainly due to decreasing temperatures in the lower stratosphere (caused by the ozone loss and carbon dioxide increase).

Global Warming by Additional Water Vapours and Cirrus Clouds

The amount of water vapour at flight altitudes north of 40° N has increased by at least 1% due to air traffic (Fransen & Peper, 1994). Because of the long residence-time, thin air, and low temperatures, a high global-warming effect results. One water vapour molecule at flight altitudes is up to 200 times more effective in this respect than a CO_2 molecule (Grassl, 1990).

An even stronger 'greenhouse' warming is caused by air-traffic water in the form of ice crystals, occurring at altitudes between 8 and 13 km at temperatures below *minus* 40°C. Only part of the water is visible as contrails. The ice crystals react in the manner of cirrus clouds — especially the 'thin' ones, which are transparent to sunlight but keep back infrared radiation from the Earth (Liou *et al.*, 1990).

In a 137-pages study about the atmospheric effects of air traffic (Fransen & Peper, 1994), it is concluded that all air-traffic climatic warming together may have caused a change locally in radiative forcing which is of the same order of magnitude as the change induced globally by all recent increases of radiatively active trace-gases due to anthropogenic emissions at the Earth's surface taken together, though calculations by models showed rather high uncertainties (Fortuin *et al.*, 1994; Wahner & Geller, 1994).

Other Emissions

According to Hofmann (1991), the anthropogenic sulphuric acid aerosols produced from sulphur dioxide in the stratosphere increased by about 50% during the preceding 10 years (excluding the increase caused by volcanoes). He thinks that air traffic is the main cause of this increase and that any future additional air traffic in the stratosphere would severely intensify the problem. In addition, air traffic is the predominant source of soot in the stratosphere, and is also of climatic relevance (Pueschel *et al.*, 1992).

Measures That Should Be Taken

International negotiations should aim at the following measures:

- Aviation-fuel taxes should be introduced internationally to restrict the growth of air traffic.
- Flights in the stratosphere should be banned in order to avoid the most severe damage to the atmosphere.

• Short-distance flights of less than about 600 to 1,000 km should be restricted (at least where railway connections are available).

• All costs of airports should be paid for by the air-traffic industry and the users and no longer by the public. All state subsidies and governmental promotions of air traffic should be abolished.

References

BECK, J.P., REEVES, C.E., LEEUW, F.A. DE & PENKETT, S.A. (1992). The effect of air traffic emissions on tropospheric ozone in the northern hemisphere. *Atmos. Environ.*, **26A**, pp. 17–29.

CARSLAW, K.S., LUO, B.P., CLEGG, S.L., PETER, T., BRIMBLECOMBE, P. & CRUTZEN, P.J. (1994). Stratospheric aerosol growth and HNO_3 gas phase depletion from coupled HNO3 and water uptake by liquid particles. *Geophys. Res. Lett.*, **21**, pp. 2479–82, illustr.

DOUGLASS, A.R., CARROLL, M.A., MORE, W.B. DE, HOLTON, J.R., ISAKSEN, I.S.A., JOHNSTON, H.S. & KO, M.K.W. (1991). *The Atmospheric Effects of Stratospheric Aircraft: A Current Consensus.* (NASA Refer. Publ. No. 1251.) NASA Office of Space Science and Applications, Washington, DC, USA: 36 pp., illustr.

DRDLA, K., TABAZADEH, A., TURCO, R.P., JACOBSON, M.Z., DYE, J.E., TWOHY, C. & BAUMGARDNER, D. (1994). Analysis of the physical state of one arctic polar stratospheric cloud based on observations. *Geophys. Res. Lett.*, **21**, pp. 2475–78, illustr.

FORTUIN, J.P.F., DORLAND, R. VAN & KELDER, H. (1994). Greenhouse effects of aircraft emissions as calculated by a radiative-transfer model. Pp. 248–54 in *Impact of Emissions from Aircraft and Spacecraft upon the Atmosphere* (Eds U. SCHUMANN & D. WURZEL), DLR-Mitteilung 94-06, Köln, Germany: 496 pp., illustr.

FRANSEN, W. & PEPER, J. (1994). *Atmospheric Effects of High-Flying Subsonic Air Traffic and Operational Measures to Mitigate these Effects.* Report by the Netherlands Directorate General of Civil Aviation and the Royal Netherlands Meteorological Institute, PO Box 90771, 2509 LT Den Haag, The Netherlands: 137 pp., illustr.

GRASSL, H. (1990). Possible climatic effects of contrails and additional water vapour. Pp. 124–37 in *Air Traffic and the Environment* (Ed. U. SCHUMANN). Springer Verlag, Berlin & Heidelberg, Germany: 170 pp., illustr.

HOFMANN, D.J. (1991). Aircraft sulphur emissions. *Nature* (London), **349**, p. 659.

HOFMANN, D.J. & OLTMANS, S.J. (1992). The effect of stratospheric water vapor on the heterogeneous reaction rate of $ClONO_2$ and H_2O for sulphuric acid aerosol. *Geophys. Res. Lett.*, **19**, pp. 2211–4, illustr.

IEA (INTERNATIONAL ENERGY AGENCY) (1995). *Oil and Gas Information 1994.* IEA, 2 Rue André Pascal, 75775 Paris Cedex 16, France: 610 pp., illustr.

JOHNSON, C., HENSHAW, J. & MCINNES, G. (1992). Impact of aircraft and surface emissions of nitrogen oxides on tropospheric ozone and global warming. *Nature* (London), **355**, pp. 69–71.

LIOU, K.N., OU, S.C. & KOENIG, G. (1990). An investigation of the climatic effect of contrail cirrus. Pp. 154–69 in Air Traffic and the Environment (Ed. U. SCHUMANN). Springer Verlag, Berlin & Heidelberg, Germany: 170 pp., illustr.

PRATHER, M.J., WESOKY, H.L., MIAKE-LYE, R.C., DOUGLASS, A.R., TURCO, R.P., WUEBBLES, D.J., KO, M.K.M. & SCHMELTEKOPF, A.L. (1992). *The Atmospheric Effects of Stratospheric Aircraft: A First Program Report.* (NASA Refer. Publ. No. 1272.) NASA Office of Space Science and Applications, Washington, DC, USA: 190 pp., illustr.

PUESCHEL, R.F., BLAKE, D.F., SNETSINGER, K.G., HANSEN, A.D.A., VERMA, S. & KATO, K. (1992). Black carbon (soot) aerosol in the lower stratosphere and upper troposphere. *Geophys. Res. Lett.*, **19**, pp. 1659–62.

SCHUMANN, U. (1994). On the effects of emissions from aircraft engines on the state of the atmosphere. *Ann. Geophysicae*, **12**, pp. 365–84, illustr.

STOLARSKY, R.S., BLOOMFIELD, P. & MCPETERS, R.D. (1991). Total ozone trends deduced from Nimbus TOMS data. *Geophys. Res. Lett.*, **18**, pp. 1015–8.

TABAZADEH, A. & TURCO, R.P. (1993). A model of heterogeneous chemical processes on the surfaces of ice and nitric acid trihydrate particles. *J. Geophys. Res.*, 98, D7, pp. 12727–40.

WAHNER, A. & GELLER, M.A. (1994). Subsonic and supersonic aircraft emissions. Pp. 11.1–11.32 in *Scientific Assessment of Ozone Depletion.* Report Nr 37, World Meteorological Organization, CH-1211 Geneva 2, Switzerland: chapters paged separately 1.1–13.36.

ROBERT A. EGLI
Consultancy Office for Chemistry of the Atmosphere
Etzelstrasse 15
CH-8200 Schaffhausen
Switzerland.

APOLOGY AND UPDATING

Although it is perhaps not such a bad record after all, being we think the first such occasion in our nearly thirty years of such journal editing, we have to apologize for getting a contributing Author's surname wrong. The case is on page 182 and the Contents table of the Summer issue of this, our final volume, where 'Venables' should be replaced by Venardos. The fault being due to our wrong manual transcription, we are truly sorry for this embarrassing error.

We would like to take this opportunity to update Professor Gilbert F. White's announcement of the 'Proposed World Water Council' in which, on page 176 of our Summer issue, Biswas *et al.* is no longer 'in prep.' but actually published, the full citation being Biswas, A.K., Mageed, Y.A., White, G.F., Chitale, M.A., Grover, B. & Jefferson, M. (1995). [Papers on World Water Council]. *International Journal of Water Resources Development*, **11**(2), pp. 101–45.

NICHOLAS POLUNIN